XXXIII Canary Islands Winter School of Astrophysics

Fundamental Physics with Galaxies (lecture II)

Kfir Blum | Weizmann Institute of Science
Dark matter

$\mathcal{M}_X$

$10^{-21} \text{ eV}$

$10^{-10} \text{ M}_\odot \sim 10^{56} \text{ eV}$
Gravity alone

$m_\chi$

$10^{-21}$ eV

$10^{-10} \ M_\odot \sim 10^{56}$ eV
Ultralight dark matter
**Ultralight dark matter (ULDM)**

Light fields (Goldstone bosons) feature in many models.  
Svrcek & Witten 2006; Arvanitaki et al 2010

**Cosmology:** field initially displaced from minimum of the potential (before/during inflation)

\[
\frac{1}{\sqrt{-g}} \mathcal{L} = \frac{1}{2} g_{\mu \nu} \partial^\mu \phi \partial^\nu \phi + m^2 f^2 \cos \frac{\phi}{f}
\]

\[
\ddot{\phi} - \frac{\nabla^2 \phi}{a^2} + m^2 \phi + 3H \dot{\phi} = 0
\]
**Ultralight dark matter (ULDM)**

Light fields (Goldstone bosons) feature in many models.  
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**Cosmology:** field initially displaced from minimum of the potential

Starts to oscillate when $t \sim 1/m$.

When $t \gg 1/m$, correct equation of state for dark matter.

\[
\ddot{\phi} - \frac{\nabla^2}{a^2} \phi + m^2 \phi + 3H \dot{\phi} = 0
\]

When $m \gg H$:

\[
\phi \approx (1 + z)^{3/2} \phi_0 \cos mt
\]

\[
\rho = \frac{\dot{\phi}^2}{2} + \frac{m^2 \phi^2}{2} \approx \frac{m^2 \phi_0^2}{2} (1 + z)^3
\]

\[
p = \frac{\dot{\phi}^2}{2} - \frac{m^2 \phi^2}{2} \approx -\rho \cos 2mt
\]
Ultralight dark matter (ULDM)

Light fields (Goldstone bosons) feature in many models.  

Cosmology: field initially displaced from minimum of the potential

\[ H_m \approx \frac{T_m^2}{M_{pl}} \approx m, \quad \phi(z_m) = \alpha f, \quad \alpha = \mathcal{O}(1) \]

Starts to oscillate when \( t \sim 1/m \).

When \( t \gg 1/m \), correct equation of state for dark matter.

\[ \rho(z = 0) \approx \frac{\rho(z_m)}{(1 + z_m)^3} \approx \frac{\alpha^2 m^2 f^2}{2 (1 + z_m)^3} \]

Contribution to energy density today:
Ultralight dark matter (ULDM)

Light fields (Goldstone bosons) feature in many models. \[ H_m \approx \frac{T_m^2}{M_{pl}} \approx m, \quad \phi(z_m) = \alpha f, \quad \alpha = \mathcal{O}(1) \]

Cosmology: field initially displaced from minimum of the potential \[ T \sim \frac{1}{m} \]

Starts to oscillate when \[ t \sim \frac{1}{m} \].

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\[ 1 + z_m \approx \frac{T_m}{T_0} \approx \sqrt{\frac{m M_{pl}}{T_0}} \]

\[ \rho(z = 0) \approx \frac{\alpha^2 T_0^3}{M_{pl}^3} \frac{f^2}{m^2} \]
Ultralight dark matter (ULDM)

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Svrcek & Witten 2006; Arvanitaki et al 2010

Cosmology: field initially displaced from minimum of the potential

Starts to oscillate when $t \sim 1/m$.

When $t \gg 1/m$, correct equation of state for dark matter.

Contribution to energy density today: 

$$\Omega_m \approx 0.3 \left( \frac{m}{10^{-21} \text{ eV}} \right)^{\frac{1}{2}} \left( \frac{f}{10^{17} \text{ GeV}} \right)^{2}$$

e.g. Hui et al, 1610.08297
Ultralight dark matter (ULDM)

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Could string theory produce such states?

\( \text{Svrcek \& Witten, hep-th/0605206} \)
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\]
e.g. Hui et al, 1610.08297

Could string theory produce many such states?

Arvanitaki et al, 0905.4720
On scales smaller than the de Broglie wavelength, **ULDM is different** than massive particle DM.

$$v^2 = \frac{GM}{R} = \frac{4\pi}{3} G \delta \rho \left( \frac{\lambda_{\text{dB}}}{2} \right)^2$$

$$\frac{\lambda_{\text{dB}}}{a} = \frac{2\pi}{amv}$$

$$\approx 6 \left( \frac{10^{-22} \text{eV}}{m} \right)^{\frac{1}{2}} \left( \frac{10^{-5}}{\delta \rho / \rho} \right)^{\frac{1}{4}} \left( \frac{1 + z}{10^3} \right)^{\frac{1}{4}} \text{Mpc}$$

$$m \gtrsim 10^{-21} \text{eV}$$

Armengaud et al 2017
On scales smaller than the de Broglie wavelength, **ULDM is different** than massive particle DM.

![Lyman-alpha forest](image)

**Figure 1:** Constraints on the scalar DM mass $m$ and fraction $F$ of the total DM density in scalar DM obtained from Lyman-$\alpha$ forest data; the two different areas indicate 2 and 3 confidence levels. These results have been obtained for the reference combination of data sets described in [16], with a physically motivated weak prior on the thermal evolution of the intergalactic medium. The regime of $m<10^{-22}$ eV has been extrapolated. DM fraction becomes small, as we will shortly see, hence the quantum pressure is also expected to be negligible there. If the quantum pressure at the nonlinear level is actually non-negligible, then it should lead to further suppression of structure formation; hence the bounds we present for the scalar DM parameters can be considered as conservative.

Following [16] we vary only $\delta_8$ (the normalization of the matter power spectrum) and the slope of the matter power spectrum $n_e$, at the scale of Lyman-$\alpha$ forest (0.005 s/km). Five different values are considered in the hydrodynamical simulations for both $\delta_8$ (in the range of [0.754, 0.904]) and $n_e$ (in the range of [2.347, 2.2674]). These parameters just described are our cosmological parameters.

There have been several studies in the past (e.g. [18], [27], [28]), that have shown that the Lyman-$\alpha$ forest is really measuring the amplitude of the linear matter power spectrum, the slope of the power spectrum, and possibly the effective running, all evaluated at a pivot scale of around 1-10 Mpc/h.

Thus $\delta_8$ and $n_e$ used are good tracers of what is actually measured. Given that all our modelling in simulations kept $\Omega_m h^2$ fixed, $\delta_8$ can be directly translated into the amplitude of linear matter power at the pivot scale (similarly to how $n_e$ was used). As pointed by [18], these matter power amplitude parameters are equivalent. The linear matter power only weakly depends on $\Omega_m h^2$, and moreover, the effects of $\Omega_m$ and $H_0$ on the linear matter power are already captured in the tracers of the amplitude ($\delta_8$) and slope ($n_e$). Therefore the constraints are not sensitive to the value of $\Omega_m$ nor $H_0$.

**See also:**
Hlozek, Marsh, Grin 1708.05681 (CMB)
Lague et al, 2104.07802 (CMB+LSS)
On scales smaller than the de Broglie wavelength, ULDM is “fuzzy”


\[ \lambda_{dB} \sim \frac{2\pi}{mv} \]

\[ v^2 \sim \frac{GM}{R} \]

\[ R \sim \lambda_{dB} \rightarrow MR \lesssim \frac{4\pi^2}{Gm^2} \]

\[ \left( \frac{M}{3 \times 10^9 M_\odot} \right) \left( \frac{R}{1 \text{ kpc}} \right) \lesssim \left( \frac{10^{-22} \text{ eV}}{m} \right)^2 \]
On scales smaller than the de Broglie wavelength, ULDM is “fuzzy”

It was suggested that Milky Way dwarf satellite galaxies may point to $m \sim 10^{-22}$ eV

Free scalar field $\phi(x, t)$

\[
\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} g^{\mu\nu} \frac{\partial \phi}{\partial x^\nu} \right) + m^2 \phi = 0
\]

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}
\]

Einstein-Klein-Gordon equations
Nonrelativistic limit

Free scalar field \( \phi(x, t) = \frac{1}{\sqrt{2m}} e^{-i mt} \psi(x, t) + cc \)

Einstein-Klein-Gordon equations

\[
\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} g^{\mu\nu} \frac{\partial \phi}{\partial x^\nu} \right) + m^2 \phi = 0
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Einstein-Klein-Gordon equations
Nonrelativistic limit

Free scalar field \( \phi(x, t) = \frac{1}{\sqrt{2m}}e^{-imt}\psi(x, t) + cc \)

Schrödinger-Poisson equations

\[ i\partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m\Phi \psi \]

\[ \nabla^2 \Phi = 4\pi G |\psi|^2 \]

Einstein-Klein-Gordon equations

\[ \frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} g^{\mu\nu} \frac{\partial \phi}{\partial x^\nu} \right) + m^2 \phi = 0 \]

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} \]
\[ \eta_{\mu \nu} = \{(1, \theta, \theta, \theta), \{\theta, -1, \theta, \theta\}, \{\theta, \theta, -1, \theta\}, \{\theta, \theta, \theta, -1\}\}; \]
\[ \chi_{\mu} = \{t, x, y, z\}; \]

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) & 0 & 0 \\
0 & 0 & a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) & 0 \\
0 & 0 & 0 & a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) \\
\end{pmatrix};
\]

\[
\begin{pmatrix}
1 + 2 \alpha GR[t, x, y, z] & 0 & 0 & 0 \\
0 & -a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) & 0 & 0 \\
0 & 0 & -a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) & 0 \\
0 & 0 & 0 & -a[t]^{-2} (1-2 \alpha GR[t, x, y, z]) \\
\end{pmatrix};
\]

\[ D_{\mu \nu} = \text{Det}[-g_{\mu \nu}]; \]

\[
i \partial_\mu \psi = -\frac{1}{2m} \nabla^2 \psi + m \Phi \psi
\]

\[
\frac{1}{\sqrt{-g}} \frac{\partial}{\partial x^\mu} \left( \sqrt{-g} g^{\mu \nu} \frac{\partial \Phi}{\partial x^\nu} \right) + m^2 \Phi = 0
\]

\[
R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} R = 8\pi G T_{\mu \nu}
\]

Schrödinger-Poisson equations

Einstein-Klein-Gordon equations
\[
\phi(t, x, y, z) = \frac{e^{-i mt}}{\sqrt{2m}} \left( \psi_r(t, x, y, z) + i \psi_i(t, x, y, z) \right) + \frac{e^{i mt}}{\sqrt{2m}} \left( \psi_r(t, x, y, z) - i \psi_i(t, x, y, z) \right);
\]

\[
\text{EOM} \phi = \frac{1}{\sqrt{\text{Dmg}}} \text{Sum} \left[ D \left( \sqrt{\text{Dmg}} \ g_{\mu \nu} \text{Upper}[[\mu, \nu]] \right) \times D \left[ \phi(t, x, y, z), x\mu[[\nu]] \right], x\mu[[\mu]] \right], \{\mu, 1, 4\}, \{\nu, 1, 4\} \right] + m^2 \phi(t, x, y, z);
\]

\[
\text{Out} = \frac{1}{a[t]^2} \left( 1 + 2 \phi(t, x, y, z) \right) \left( \sinh[mt]) \left( \psi_{i(0,0,2)}[t, x, y, z] + \psi_{i(0,2,0)}[t, x, y, z] + \psi_{i(2,0,0)}[t, x, y, z] \right) + \right.
\]

\[
\left. \cos[mt] \left( \psi_{r(0,0,2)}[t, x, y, z] + \psi_{r(0,2,0)}[t, x, y, z] + \psi_{r(2,0,0)}[t, x, y, z] \right) \right) + \ldots
\]

\[
i \partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m\phi \psi
\]

\[
\nabla^2 \phi = 4\pi G |\psi|^2
\]

\[
R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}
\]

Schrödinger-Poisson equations

Einstein-Klein-Gordon equations
\( \Phi[t, x, y, z] = \frac{e^{-i \Delta t}}{\sqrt{2m}} (\psi[r[t, x, y, z] + i \psi[i[t, x, y, z]]) + \frac{e^{i \Delta t}}{\sqrt{2m}} (\psi[r[t, x, y, z] - i \psi[i[t, x, y, z]]) ; \)

\[
\text{EOM} = \frac{1}{\sqrt{\text{Dmg}}} \text{Sum} \left[ D \left[ \sqrt{\text{Dmg}} \ g_{\mu \nu} \text{Upper} \left[ \left[ \mu, \nu \right] \right] \times D \left[ \phi[t, x, y, z], x_{\mu \left[ \nu \right]}, x_{\mu \left[ \mu \right]} \right], \left[ \mu, 1, 4 \right], \left[ \nu, 1, 4 \right] \right] + m^{2} \phi[t, x, y, z] ; \right]
\]

Adding \( i \times \text{(Sin part)} + \text{(Cos part)}:\)

\[
i \partial_{t} \psi = - \frac{1}{2m} \nabla^{2} \psi + m \Phi \psi + \frac{1}{2m} \partial^{2}_{t} \psi - 2 \psi \partial_{t} \Phi - \frac{2}{m} \partial_{t} \Phi \partial_{t} \psi r + 2 i \partial_{t} \Phi \left( \psi r - \frac{1}{m} \partial_{t} \psi i \right) - \frac{1}{m} \Phi \nabla^{2} \psi + \ldots
\]

Subleading corrections

\[
i \partial \psi = - \frac{1}{2m} \nabla^{2} \psi + m \Phi \psi
\]

\[
\nabla^{2} \Phi = 4\pi G |\psi|^{2}
\]

Schrödinger-Poisson equations

\[
R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} R = 8\pi G T_{\mu \nu}
\]

Einstein-Klein-Gordon equations
An aside: Madelung representation

\[ i\partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m\Phi \psi \]

\[ \psi = \sqrt{\rho} e^{i\theta} \quad \nabla \theta = mv \]

\[ \dot{\rho} + \nabla \cdot (\rho v) = 0 \]

\[ \dot{v} + (v \cdot \nabla) v = -\nabla \Phi + \frac{1}{2m^2} \nabla \left( \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} \right) \]
Numerical simulations

\[ i\partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m\Phi \psi \]

\[ \nabla^2 \Phi = 4\pi G |\psi|^2 \]

Schive et al 2014

Mocz et al 2017

Levkov et al 2018

Veltmaat et al 2018

see Supplementary material S1.4 for derivation. Here
Inner part of simulated galaxies forms a **core**

\[
i \partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m \Phi \psi
\]

\[
\nabla^2 \Phi = 4\pi G |\psi|^2
\]
Inner part of simulated galaxies forms a core

Simulation: L. Teodori, M. Gorghetto
Coherent ground state: \( \psi(x, t) = \left( \frac{mM_{pl}}{\sqrt{4\pi}} \right) e^{-i\gamma mt} \chi(r) \)

\[
\begin{align*}
    i\partial_t \psi &= -\frac{1}{2m} \nabla^2 \psi + m\Phi \psi \\
    \nabla^2 \Phi &= 4\pi G |\psi|^2
\end{align*}
\]

\[
\begin{align*}
    \partial_r^2 (r\chi) &= 2r (\Phi - \gamma) \chi \\
    \partial_r^2 (r\Phi) &= r\chi^2
\end{align*}
\]

Numerical simulations find the ground state.
Coherent ground state: \( \psi(x, t) = \left( \frac{mM_{pl}}{\sqrt{4\pi}} \right) e^{-imt} \chi(r) \)

\[ i\partial_t \psi = -\frac{1}{2m} \nabla^2 \psi + m\Phi \psi \]

\[ \nabla^2 \Phi = 4\pi G |\psi|^2 \]

\[ \frac{\partial^2}{\partial r^2} (r\chi) = 2r (\Phi - \gamma) \chi \]

\[ \frac{\partial^2}{\partial r^2} (r\Phi) = r\chi^2 \]

Numerical simulations find the ground state.

This is reminiscent of BEC:
Gross-Pitaevskii with nonlocal interaction:

\[ i\partial_t \psi(x) = -\left( \frac{1}{2m} \nabla^2 + Gm \int d^3y \frac{|\psi(y)|^2}{|x-y|} \right) \psi(x) \]
Core — halo relation

Schive et al
1406.6586, 1407.7762
Core — halo relation

\[ \frac{E}{M \mid_{\text{core}}} = \frac{E}{M \mid_{\text{halo}}} \]

Bar, et al 1805.00122

\[ M = \int d^3x |\psi|^2 \]

\[ E = \int d^3x \left( \frac{|\nabla \psi|^2}{2m^2} + \frac{\Phi |\psi|^2}{2} \right) \]

Schive et al 1406.6586, 1407.7762

\[ \frac{E}{M} \mid_{\text{halo}} \]

\[ (|E'|/M')^{1/2} \]
Core — halo relation

Bar, et al 1805.00122

\[
\frac{E}{M}_{\text{core}} = \frac{E}{M}_{\text{halo}}
\]

\[
M = \int d^3 x |\psi|^2
\]

\[
E = \int d^3 x \left( \frac{|\nabla \psi|^2}{2m^2} + \frac{\Phi |\psi|^2}{2} \right)
\]

Schive et al 1406.6586, 1407.7762
Core — halo relation

Bar, et al 1805.00122, 1903.03402

\[
\frac{K}{M}_{\text{core}} = \frac{K}{M}_{\text{halo}}
\]

K/M: kinetic energy/mass.

\[
M = \int d^3x \mid \psi \mid^2
\]

\[
E = \int d^3x \left( \frac{\mid \nabla \psi \mid^2}{2m^2} + \frac{\Phi \mid \psi \mid^2}{2} \right)
\]

\[
K = \int d^3x \frac{\mid \nabla \psi \mid^2}{2m^2} = -E
\]

Schive et al 1406.6586, 1407.7762
Dynamical relaxation is fast enough for \( m \lesssim 10^{-21} \) eV.

\[
\tau = \tau_U \\
\tau = 0.1\tau_U
\]

\[
\tau \sim \frac{\sqrt{2}}{12\pi^3} \frac{m^3\sigma^6}{G^2\rho^2\ln \Lambda}
\]
Core — halo relation

\[
\frac{K}{M} \bigg|_{\text{core}} = \frac{K}{M} \bigg|_{\text{halo}}
\]

References [9] (Schive 2014) and [29] (Chan 2017).

In Fig. 4 we compare our results to two soliton+halo configurations from the simulations of [9] and [29] (for [9], thus the soliton relevant for that host halo.

In the rest of this paper, when we refer to Eq. (49), we take the largest halo, and for [29] we take the initial state of Case C. To calculate the soliton, we read Eq. (49) by unity, and replacing \( \max \) we set the RHS to unity. Approximating the RHS of Eq. (29), the peak circular velocity of a host halo allows to predict the scale parameter \( V_{\text{circ}} \) instead of max of the numerically extracted halo rotation curves (solid lines), use it instead of max of the usual inner NFW form.

Building on Eq. (35), we expect in general that for the manifestation of the empirical Eq. (35) that is not tied to a particular parametrisation of the host halo profile a direct comparison to numerical results.

In App. A we address this question, by analysing the eigenvalues of the rotation curve in the intermediate region between the two peaks, but not our general conclusion that if the soliton-host halo relation of [9, 10] is not enough to resolve the discrepancy highlighted by the smaller sample of galaxies in Fig. 5.

We emphasize that in using Eq. (49) to predict the soliton, we set the RHS of that equation to unity, and thus the factor of velocity to o lines), use it instead of max of the numerically extracted halo rotation curves (solid lines), use it instead of max of the usual inner NFW form.

For lower particle mass, the soliton is not enough to resolve the discrepancy highlighted by the smaller sample of galaxies in Fig. 5 being accidental outliers. We do not pursue it further, one reason being that this range of small being that this range of small

Rotation curves from simulations:
Core — halo relation

\[
\frac{K}{M}_{\text{core}} = \frac{K}{M}_{\text{halo}}
\]
(Estimated) radially-averaged mass profile of the Milky Way
Massive cold dark matter:

thought to affect outer part of rotation curve
ULDM:

Affects the inner part of rotation curve
ULDM:

Affects the inner part of rotation curve
ULDM:

Affects the inner part of rotation curve
ULDM:

Affects the inner part of rotation curve

A bump in the MW rotation curve?!
Schive et al 1406.6586, 1807.08153
Zhi Li et al 2001.000318

Bar et al 1805.00122
ULDM:

Affects the inner part of rotation curve

there are probably about $10^9$ stars in there…
the extent of the stars 

gas is still detected is UGC 1281 has a low SFR. 
ever, in the case of UGC 1281 this seems unlikely because no 
internal dust extinction, especially in the edge-on orientation. How-
of the galaxy. 

of the galaxy might be caused by a ring-like structure or central 

axis at a radial distance of 

$H_\text{II}$

⃝

2011 The Authors, MNRAS

In our data the maximum distance to the mid-plane where diffuse 

Continuum image in the red from the DSS 2 overlaid with contours of our integrated $H_\text{II}$ =

the rotational velocity, the density distribution of the ionized gas, 

fitted to each bin (see Section 3.1.1). This is by no means equal to 

Fig. 4 shows the velocity field of the PPAK observations. This ve-

data are much more extended than the observational beam. 

of the data. In this figure it is easily observed that the wings of the 

$m = 10^{-22}$ eV 

Figure 3. 

3448

P. Kamphuis et al.

$H_\text{II}$ regions as well as the diffuse 

HST $H_\text{II}$ 18 arcsec, van Zee (2000); 

´ılchez 2004) and therefore 

extends up to 70 arcsec (1.8 kpc) on both sides 

1 arcsec, de Vaucouleurs et al. (1992)]. If we fit an 

23 arcsec, de Vaucouleurs et al. (1992)

0.03 kpc) assuming that 

4 arcsec) assuming that 

$0.01$ kpc) and 

$2011$ RAS

Obtained through the NASA extragalactic data base.

Furthermore, the $H_\text{II}$ distribution displays a central depression.

N $H_\text{II}$ distribution. It warps 

$H_\text{II}$ structed by adding all the channels of the Circular Beam data 

contours of our integrated $H_\text{II}$ flux map of UGC 1281 (see text). The black contours are 

intensity profiles of the observed $H_\text{II}$, $P$. K a m p h u i s e t a l .

regions (Garc´ıa-Ruiz, Sancisi & Kuijken 2002) but bends back to the 

initially shows the normal S-shape observed in many edge-on galax-

ies (Garc´ıa-´ılchez 2004) but bends back to the 

This warp was already observed by Garc´ıa-´ılchez 2004) but bends back to the 

$H_\text{II}$ axis in Fig. 6.

velocities along the major axis. The left-hand panel shows the 

Velocities along the major axis. The left-hand panel shows the 

$H_\text{II}$ velocities: black symbols are the $H_\text{II}$ 

Kuzio de Naray et al. (2006) were not able to trace emission as far out in 

rotation curve obtained from the modelling (see Section 4). Kuzio 

does not bin the data and the lower sensitivity of the DensePak IFU.

radius with their observations. Since their exposure time and fibre 

do not bin the data and the lower sensitivity of the DensePak IFU.

de Naray et al. (2006) with the DensePAK IFU (blue symbols) and the 

impossible to confidently fit the intrinsic shape of the emission line.

was chosen because with a channel separation of 70 km s$^{-1}$ 

velocity we are referring to this mean velocity unless otherwise noted.

and the opacity of the dust. From here on whenever we mention ve-

axis in Fig. 6.
Where is the core?

This *could* have been spectacular…
$m_X$

$10^{-21}$ eV

A lower limit on the mass of dark matter, with gravity alone
A lower limit on the mass of dark matter, with gravity alone

$\mu_X$

$10^{-21} \text{ eV}$

There are complimentary observables
There are complimentary observables

Kobayashi et al 2017; Armengaud et al 2017; …
There are complimentary observables

$\mathcal{m}_X$

$10^{-21} \text{eV} \rightarrow 10^{-18} \text{eV}$

Khmelnitsky & Rubakov 1309.5888,
Poryako et al 1810.03227 (Parkes pulsar timing array)
There are complimentary observables Bar et al 2019; Amorim et al 2019 (GRAVITY),...
There are complimentary observables

$10^{-21} \text{ eV} \rightarrow 10^{-18} \text{ eV}$

Bar et al 2019; Amorim et al 2019 (GRAVITY)
There are complimentary observables  

Bar et al 2019; Amorim et al 2019 (GRAVITY),…

BH shadow ~ $10^{10}$ km
Stellar velocities ~ $10^{16}$ km
…Nothing in between.

$10^{-21}$ eV $\rightarrow$ $10^{-18}$ eV

ESO 2008, 16 year time lapse

Event Horizon Telescope 2022

M87 $\rightarrow$

ESO & NASA/CFHT, J.-C. Cuillandre

Event Horizon Telescope 2019

Gebhardt et al 2011

Velocity dispersion vs. radius for M87. The black points are the

LOSVD is defined in 15 velocity

plots the velocity dispersion from

Gebhardt et al 2000a and

we plot

spectra into the models. Table

the LOSVD in a parameterized form as Gauss–Hermite moments,

directly. However, it is sometimes convenient to express the

uncertainty.

We input 10^7 LOSVDs in the dynamical models. These

No fitted at any very high (50 – 100 pixels element).

The four features of the spectra

are fitted into the models.

There are complimentary observables

Bar et al 2019; Amorim et al 2019 (GRAVITY),…

BH shadow ~ $10^{10}$ km
Stellar velocities ~ $10^{16}$ km
…Nothing in between.
$m_X$

$10^{-21} \text{eV} \rightarrow 10^{-18} \text{eV}$

Thin, optically-thick disk (Luminet 1978)

Model-dependence in accurate interpretation: e.g. Gralla, Holz, Wald 1906.00873

\[
\left(\frac{du}{d\varphi}\right)^2 + u^2 (1 - 2u) = \frac{1}{b^2}
\]

\[
u = \frac{1}{r} \quad \text{units of GM}
\]
$m_X$

$10^{-21} \text{eV} \rightarrow 10^{-18} \text{eV} ?$

Thin, optically-thick disk (Luminet 1978)

Model-dependence in accurate interpretation: e.g. Gralla, Holz, Wald 1906.00873

Optically-thin spherical gas (Flacke, Melia, Agol 2000)
\[ m_X \]

\[ 10^{-21} \text{ eV} \rightarrow 10^{-18} \text{ eV} \]

SMBH effect: e.g. Annuli, Cardoso, Vicente 2009.00012

Bar et al, 1905.11745

M87 SMBH

Soliton mass in $M_\odot$

Particle Mass in eV
$m_X$

$10^{-21}$ eV $\rightarrow$ $10^{-18}$ eV  

SMBH effect: e.g. Annulli, Cardoso, Vicente 2009.00012

Bar et al., 1905.11745

Ly-α/LSBs

BH absorption

M87 SMBH

CWD

S2

BH absorption

Soliton mass in $M_\odot$

Particle Mass in eV

Soliton mass in $M_\odot$

mass in eV
Ultralight dark matter

Gravity alone

$m_\chi$

$10^{-21}$ eV

$10^{-10}$ M$_\odot \sim 10^{56}$ eV

Figure 3. Binning scheme in M87 for the NIFS data only. Although this particular frame does not have data for each bin, the dithered set fills all bins. Data in the mirror bins around the major axis are added to the bins shown.

Figure 4. Spectra at three different radii. The top is from $0\prime\prime.08 < R < 0\prime\prime.18$, the middle is from $0\prime\prime.18 < R < 0\prime\prime.3$, and the bottom is from $R = 0\prime\prime.6$. The black line is the spectrum and the smooth red line is the best-fit template convolved with the best-fit LOSVD. The dashed lines are those regions excluded from the fit due to high sky contamination. The spectrum at the top, which comes from the central region, is not used in the fit due to AGN contamination. The velocity dispersion obtained from the fits shown in red, from top to bottom, is 480 km s$^{-1}$, 480 km s$^{-1}$, and 445 km s$^{-1}$, and the S/N per pixel in each is 30, 63, and 91.

Figure 5. Velocity dispersion vs. radius for M87. The black points are the NIFS data. The red points are the VIRUS-P data from Murphy et al. (2011), and the blue points are from the SAURON data. The multiple points at each radius represent the various position angles. The solid line is the best-fit model, convolved to the appropriate PSF. For the dynamical model, we include the predicted dispersion within $0\prime\prime.18$. (A color version of this figure is available in the online journal.)

The technique is described in Gebhardt et al. (2000a) and Pinkney et al. (2003). The LOSVD is defined in 15 velocity bins of 260 km s$^{-1}$. There is a smoothing parameter applied to the LOSVD, but given the high S/N for these spectra, the smoothing has little effect on the extractions; thus, there is only a modest correlation between adjacent velocity bins. We use Monte Carlo simulations to determine the uncertainties in the LOSVD. The S/N for these spectra determine the noise to be used in the Monte Carlo simulations; from 1000 realizations of each spectrum, we generate an average LOSVD and the 68% uncertainty.

The dynamical modeling uses the non-parametric LOSVD directly. However, it is sometimes convenient to express the LOSVD in a parameterized form as Gauss–Hermite moments, to show the radial run of the kinematics, and to compare the data with the models. Table 2 shows the first four Gauss–Hermite moments for the NIFS data. Figure 5 plots the velocity dispersion versus radius, where the dispersion is measured from a Gauss–Hermite fit to the LOSVDs. Figure 5 plots all of the data at each radius, and there are between 1 and 10 angular bins at each radius; thus, there are multiple points at nearly all radii in the figure. There is no rotation seen at a significant level in the NIFS data.

We input 107 LOSVDs in the dynamical models. These LOSVDs come from 40 spatial bins from the NIFS data, 25 from the SAURON data, and 42 from the large radial data of Murphy et al. (2011). The data in Murphy et al. come from the IFU VIRUS-P, where we have nearly complete angular coverage. The S/N for these spectra is very high (50 – 100 per resolution element). The solid line in Figure 5 plots the velocity dispersion from the best-fit dynamical model. The model generates LOSVDs, and their dispersions come from Gauss–Hermite fits to those LOSVDs. For the dynamical model dispersions, we average along angles at a given radius for clarity. In Figure 5, we plot both the NIFS and VIRUS-P dispersions, which have different PSFs. The model is convolved to each of the PSFs, and the plotted dispersions include the convolution.
Thank you!
Some facts about solitons

Continuous family of ground state solutions, characterised by one parameter

Let \( \chi_1(r) \) be defined to satisfy \( \chi(0) = 1 \), vanishing at infinity w/ no nodes.

\[
M_1 = \frac{M_{pl}^2}{m} \int_0^\infty dr r^2 \chi_1^2(r)
\approx 2.79 \times 10^{12} \left( \frac{m}{10^{-22} \text{eV}} \right)^{-1} M_\odot
\]

Other solutions obtained by scaling

\[
\begin{align*}
\chi_\lambda(r) &= \lambda^2 \chi_1(\lambda r), \\
\Phi_\lambda(r) &= \lambda^2 \Phi_1(\lambda r), \\
\gamma_\lambda &= \lambda^2 \gamma_1, \\
M_\lambda &= \lambda M_1 , \\
x_{c\lambda} &= \lambda^{-1} x_{c1}
\end{align*}
\]